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OBSERVATIONAL AND THEORETICAL STUDIES OF LOW-MASS STAR FORMATION

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Annual Progress Report - Grant NAGW-3401

In the past year we have pursued studies of low-mass star formation in two main ways: (1) analysis of evolutionary development of young stellar objects (YSOs), by quantifying the relationship between T_{bol} and age, by comparison of the bolometric luminosity-temperature (BLT) diagram in the nearest star-forming complexes Taurus, Ophiuchus, Lupus, Chamaeleon, and Corona Australis, and by development of models of evolution of protostars in the BLT diagram; and (2) high-resolution observations of dense gas tracers in the star-forming dense cores L1527 and L483, showing kinematic evidence for gravitational infall in lines of C_3H_2 and H_2CO.

1. Evolution of Young Stellar Objects.

The Hertzsprung-Russell (HR) diagram is one of the most powerful tools in the study of stellar evolution. But it is nearly useless for studying some of the most interesting YSOs, those younger than about 1 Myr. At these early ages, much of the emission from the YSO passes through heavy circumstellar obscuration, so that the optical lines needed to determine the photospheric temperature are invisible, and most of the luminosity emerges in the infrared. To quantify the evolution of protostars and pre-main sequence stars in a continuous way, the "bolometric temperature" T_{bol} was introduced (Myers & Ladd 1983; ML). T_{bol} is the temperature of a blackbody having the same mean frequency as the observed spectrum, and T_{bol} is easily computed from the observed spectrum F_ν:

$$T_{bol} = \frac{\varsigma(4)\, h\, \overline{\nu}}{4\varsigma(5)\, k} = 1.25 \times 10^{-11} \frac{\int_0^\infty d\nu\, \nu\, F_\nu}{\int_0^\infty d\nu\, F_\nu} \quad \mathrm{K\ Hz^{-1}}$$

Here h and k are Planck's and Boltzmann's constants, and $\zeta(n)$ is the Riemann zeta function of argument n. ML showed that for 125 YSOs in Taurus-Auriga, T_{bol} increases monotonically from "class zero" protostars dominated by far infrared and submillimeter emission, to "class I" protostars dominated by far infrared emission, to "class II" YSOs, primarily classical T Tauri stars with strong H α emission, to "class III" YSOs, primarily weak-line T Tauri stars known by their x-ray emission. This increase in T_{bol} corresponds to the dissipation of natal circumstellar dust. Thus T_{bol} is a quantitative measure of the "spectral evolution" described by Adams, Lada & Shu (1987).

In this period, we have made three contributions based on these ideas. We showed (a) for YSOs in Taurus-Auriga, T_{bol} increases with age since the onset of infall, according to detailed YSO age estimates based on models of dynamical infall (Kenyon et al 1993) and of hydrostatic settling (d'Antona & Mazzitelli 1994). This increase is shown in Figure 1, and is described by

$$\log T_{bol} = 1.02 \pm 0.32 + (0.29 \pm 0.07) \log \mathrm{age} \quad (1.7 < \log T_{bol} < 3.0)$$

$$\log T_{bol} = 2.79 \pm 0.15 + (0.11 \pm 0.02) \log \mathrm{age} \quad (3.0 < \log T_{bol} < 3.8)$$

(Chen et al 1995a). We constructed BLT diagrams for the five nearest star-forming complexes, and found distinct differences among them. From Lupus to Chamaeleon to Taurus to Corona Australis to Ophiuchus, the median L_{bol} increases, while the median T_{bol} decreases, as shown in Figure 2. These trends indicate an increasing proportion of young, embedded sources from Lupus to Ophiuchus (Chen et al 1995b).

A theoretical framework was developed for interpreting evolution of YSOs, according to the infall models of Adams & Shu (1986). In the wavelength range 3-30 μm where the absorption coefficient is approximately independent of wavelength, a photospheric approximation to the surface of unit optical depth, viewed from the outside, leads to the relations

$$L_{bol} \sim T^{8/3}\, T_{bol}^{4/3}$$

$$L_{bol} \sim M^{8/5}\, T_{bol}^{-4/5}$$

$$L_{bol} \sim t^{16}\, T_{bol}^{-20}$$

Here T is the gas kinetic temperature, M is the mass of the star-disk system, and t is the time since the onset of infall. Two of these three relations are independent, since $M = (kT/m)^{3/2}\, t/G$. These relations provide a good fit to detailed calculations of the spectra of class I protostars, according to the models of Adams, Lada and Shu (1987). The three relations above represent lines of constant temperature, constant mass, and constant time. Figure 3 shows these lines. It shows that star-forming cores with constant temperature evolve toward the upper left on the BLT diagram, crossing lines representing progressively larger star-disk mass and later times, up to a few times 0.1 Myr (Myers, Adams, & Schaff 1995).

2. Kinematic Evidence of Gravitational Infall in L1527 and L483.

We carried out observations of 8 lines, primarily of C_3H_2 at wavelengths of 4 mm at the 37-m telescope of Haystack Observatory, and of H_2CO at wavelengths of 2 mm and 1mm at the IRAM 30-m telescope. These observations were intended to obtain kinematic evidence of circumstellar motions in the star-forming dense cores L1527 and L483. Line profiles with spectral resolution 0.05 km s^{-1}, and angular resolution 12-27" were observed as functions of line optical depth and map position, especially along and across the directions of the bipolar outflow from each source.

The main result of these observations is that the line profiles show three properties which probably indicate infall, as opposed to outflow or rotation. The profiles become more asymmetric and their centroid velocities become bluer, as map positions approach each protostar. The H_2CO profiles show two-peak asymmetry, with the blue peak brighter than the red peak, as seen toward the protostar in B335 by Zhou et al (1993). This "infall asymmetry" is the best-known signature of graviational infall motions. This spectral asymmetry is an extreme case of a more general and more prevalent blueing of the centroid velocity, which is expected for models of radial infall, where the line optical depth exceeds unity and where the excitation temperature increases inward (e.g. Zhou et al 1993, Walker et al 1995). In such models, the blue part of the line profile arises in the rear of the cloud, the red part arises in the front of the cloud, and the self-absorption dip, if present, arises from low-velocity, low-excitation foreground gas. Figure 4 shows this blueing of the centroid velocity in L1527 for the 2 mm line of H_2CO and the 4 mm line of C_3H_2, but not for the optically thinner 3 mm line of N_2H^+ (Myers et al 1995).

The blueing of the centroid velocity is not expected for outward motions, where the centroid velocity should become redder toward the protostar. It is also not expected for rotation, shear, or bipolar outflow, where the centroid velocity should become redder when approaching the protostar from one direction, and bluer when approaching from the opposite direction (e.g. Adelson & Leung 1978).

These observations provide a new signature of infall motions, more general than the two-peak asymmetry seen in some lines, and indicate that L1527, and probably L483, are undergoing infall motions in a manner similar to that of B335.

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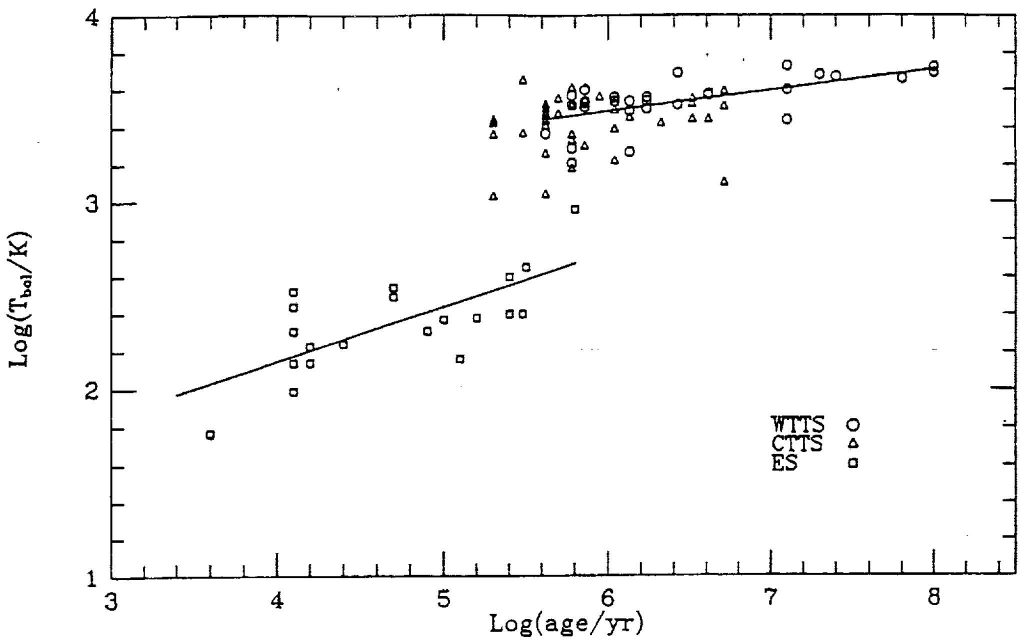
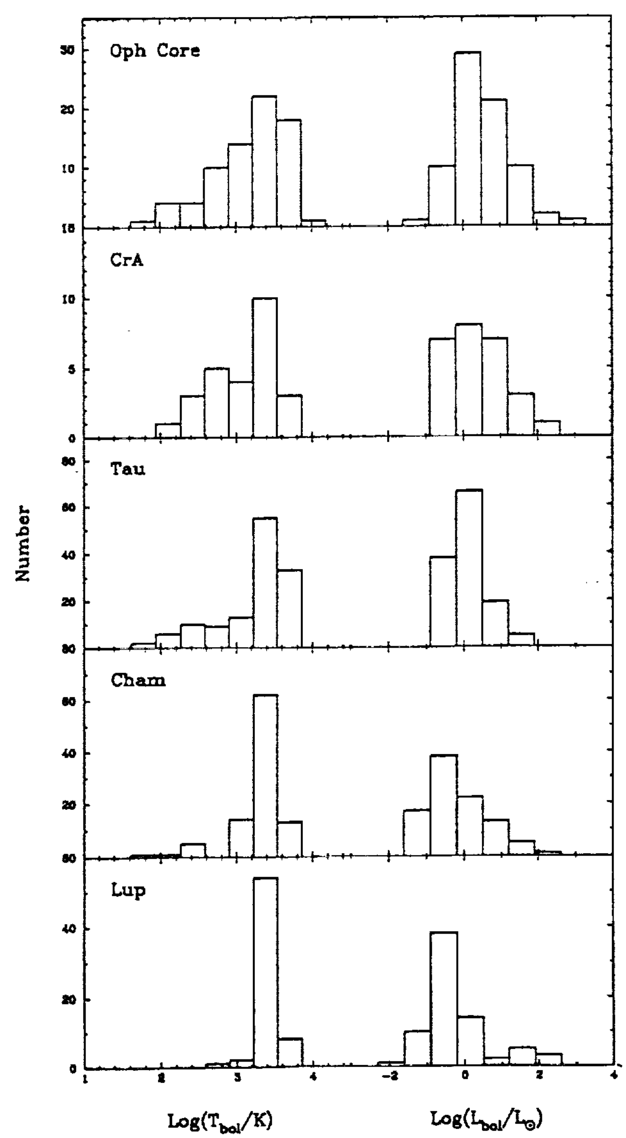


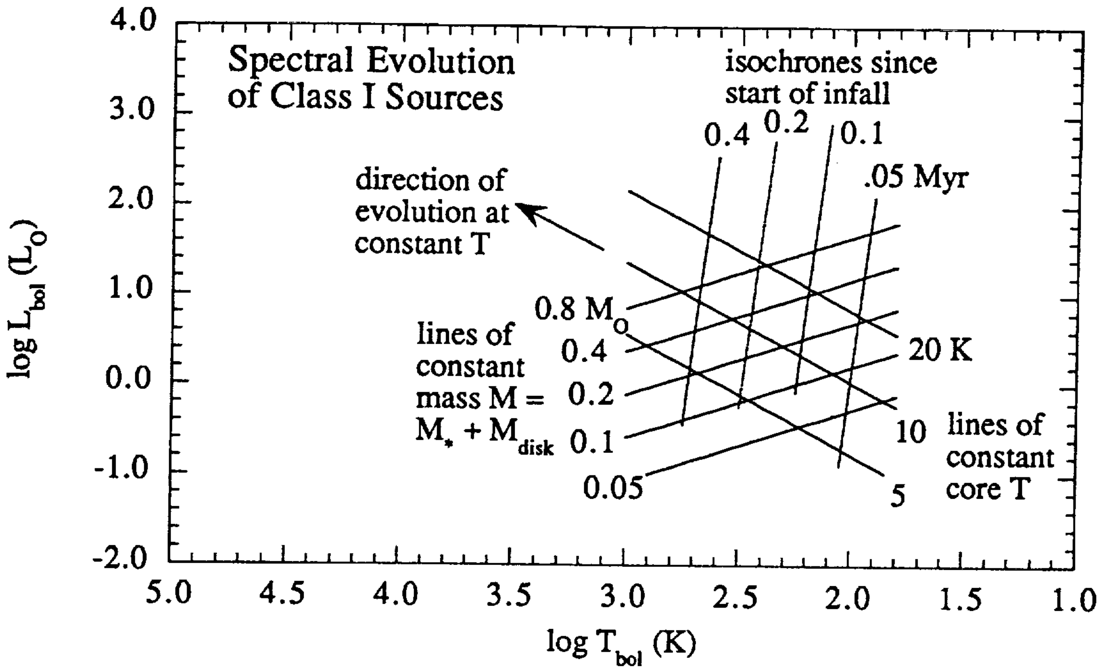
Log(T_bol/K)
Log(age/yr)
WTTS
CTTS
ES

1,



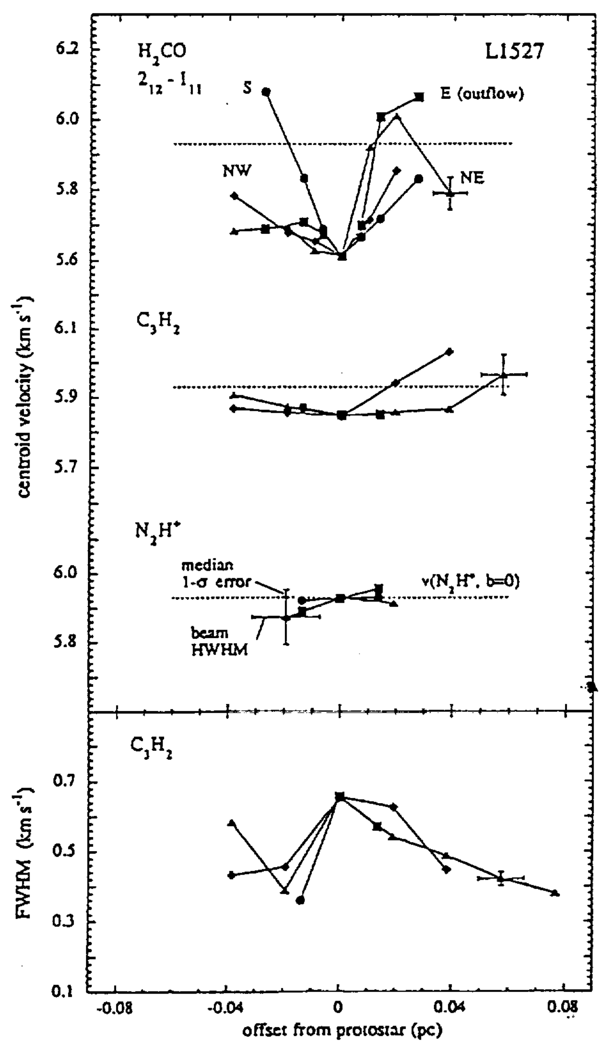
Oph Core
CrA
Tau
Cham
Lup
Number
Log(T_bol/K)
Log(L_bol/L_⊙)

2,



Spectral Evolution
of Class I Sources
isochrones since
start of infall
0.4 0.2 0.1
.05 Myr
direction of
evolution at
constant T
0.8 M_O
0.4
0.2
0.1
0.05
lines of
constant
mass M =
$M_* + M_{disk}$
20 K
10
5
lines of
constant
core T
log L_{bol} (L_O)
log T_{bol} (K)

3.



H_2CO
$2_{12} - 1_{11}$
L1527
S
E (outflow)
NW
NE
C_3H_2
N_2H^+
median
1-σ error
beam
HWHM
$v(N_2H^+, b=0)$
centroid velocity (km s^{-1})
C_3H_2
FWHM (km s^{-1})
offset from protostar (pc)

4.